EVALUATION OF CRACK ARREST FRACTURE TOUGHNESS OF PARENT PLATE, WELD METAL AND HEAT AFFECTED ZONE OF BIS 812 EMA SHIP PLATE STEEL

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Abstract

The steel chosen for the pressure hull of the Collins class submarine has undergone evaluation to compare the crack arrest fracture toughness, K_{Ia}, of the parent plate with that of weld metal and heat affected zone. The tests were conducted over a range of sub-zero temperatures on specimens slightly outside the ASTM standard test method specimen configuration. Shallow face grooved specimens were used to vary the propagating crack velocity from that of non face grooved specimens and determine if K_{Ia} is sensitive to changes in crack velocity.

The weld metal, heat affected zone (HAZ) and parent plate were assessed to determine if the welding process had a deleterious effect on the crack arrest properties of this particular steel. Tests on each of these regions revealed that, for the combination of parent plate, welding procedure and consumables, no adverse effect on crack arrest properties was encountered. Crack arrest fracture toughness of the weld metal and HAZ was superior to that of the parent plate at comparable temperatures.

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1. *Introduction*

The Royal Australian Navy is currently upgrading its submarine fleet with six Kockums-designed type 471 diesel electric submarines. These submarines will be known locally as the Collins class and will replace the existing Oberon class as they become operational from mid 1995.

A policy requirement for this procurement was that the submarines be constructed in Australia, using a locally modified Swedish pressure hull steel. The steel is designated BIS 812 EMA and manufactured by Bisalloy Steels. The steel meets the fracture control philosophy requirements [1,2] for the pressure hull with specified levels of tensile strength, charpy impact energy, dynamic tear energy and explosion bulge performance, but a quantitative dynamic fracture parameter was not a requirement.

The objective of this work was to assess the dynamic fracture toughness of the parent plate and the weld metal and heat affected zone (HAZ) regions produced during the welding process. Welding is the primary fabrication process used for submarine construction and may introduce changes in microstructure, weld defects and/or residual stress fields and the dynamic fracture behaviour of a welded structure may change due to the introduction of one or more of these effects.

Although dynamic fracture toughness assessment is not a requirement for qualification for this steel, crack arrest fracture toughness, K_{Ia}, can be used to characterise the dynamic properties because it provides a quantitative basis for comparison of crack propagation and arrest properties in high toughness steels. Additionally, the technique for measuring K_{Ia} is relatively simple only requiring

the crack mouth opening displacement following arrest and the crack jump length to be measured.

Crack arrest fracture toughness assessment of a similar strength ship plate steel [3] has shown that the crack arrest toughness was approximately 30% of the initiation fracture toughness, K_{Ic}, indicating the stress intensity factor at the tip of a propagating crack must fall appreciably in order for the crack to arrest.

Ideally, high K_{Ia} values assure an acceptable level of dynamic toughness and as such, an ability to arrest propagating cracks.

2. *Material*

BIS 812 EMA is a low carbon, micro-alloyed, nickel-chromium-molybdenum, quenched and tempered steel. Titanium and vanadium are added, as nitride/carbide formers, to prevent excessive grain growth in the HAZ during welding. The mechanical properties and chemical composition are listed in Tables 1 and 2 respectively.

Table 1: *Mechanical properties of BIS 812 EMA steel*

Yield Strength:		690 MPa
UTS:		780-930 MPa
Elongation:		18%
Charpy V energy:		
	Transverse orientation	90 J at -18°C
		75 J at -60°C
		41 J at -85°C

Table 2: *Chemical composition (weight %) of BIS 812 EMA steel*

C	Mn	Si	P	S	Cr	Ni	Cu	Mo
0.13	0.93	0.24	0.011	0.002	0.48	1.28	0.2	0.39

V	Ti	Nb	Al	B	Ca	N	O
0.02	0.01	0.01	0.07	0.002	< 3 ppm	0.009	0.001

The parent plate microstructure is a fine grained, fully transformed tempered martensite as shown in Figure 1.

Figure 1: Martensitic microstructure of BIS 812 EMA. (X500, etchant: nital)

2.1 Welding

Welding of BIS 812 EMA steel was performed using multipass weld runs on a K-type weld preparation profile as shown in Figure 2. The material was supplied in the welded condition by the Australian Submarine Corporation (ASC). The welding procedure employed [4] by ASC was manual metal arc welding (MMAW) for the initial root pass and submerged arc welding (SAW) for subsequent fill and cap passes. Figure 3 shows the weld sequence and total number of passes. Two welded coupons were supplied and each was subjected to ultrasonic, x-ray and magnetic particle non destructive test procedures to ensure minium defect levels.

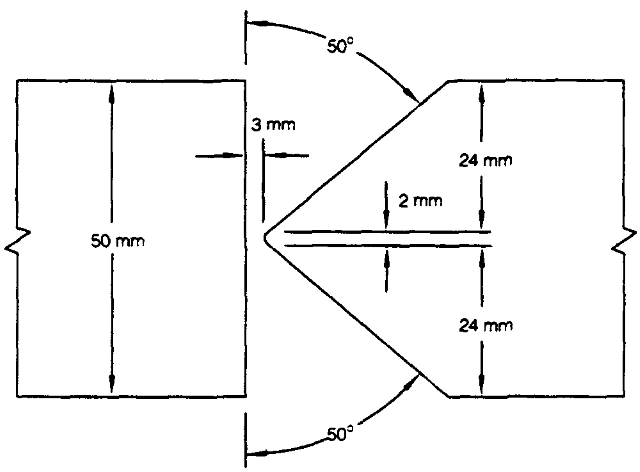


Figure 2: K-type weld preparation.

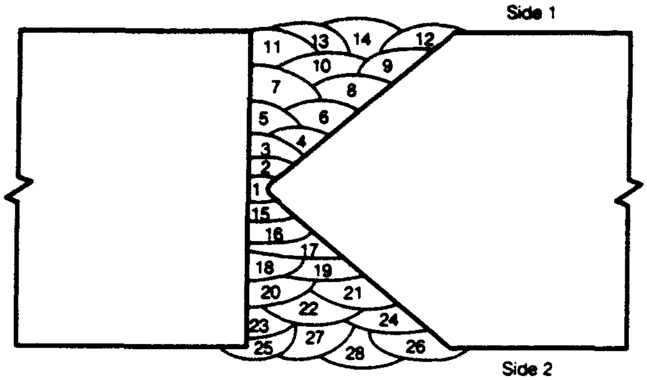


Figure 3: Weld sequence and number of passes [4] for BIS 812 EMA K-preparation weld.

2.2 The Heat Affected Zone

The heat affected zone of a multipass weld contains a wide range of microstructures that are dependent on the welding procedure and steel chemistry.

Multipass welds are further complicated by the interaction of successive weld passes. Each successive weld pass alters the microstructure produced by its predecessor. A macrograph of a K-prep. weld (BIS 812 EMA) illustrating the result of successive weld pass interactions is shown in Figure 4. Another critical aspect of the weld zone is the residual stress fields produced by thermal input and mechanical constraint, although this may be minimised by careful control of welding parameters such as heat input and pre-heat.

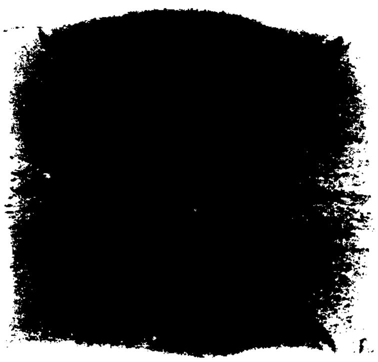
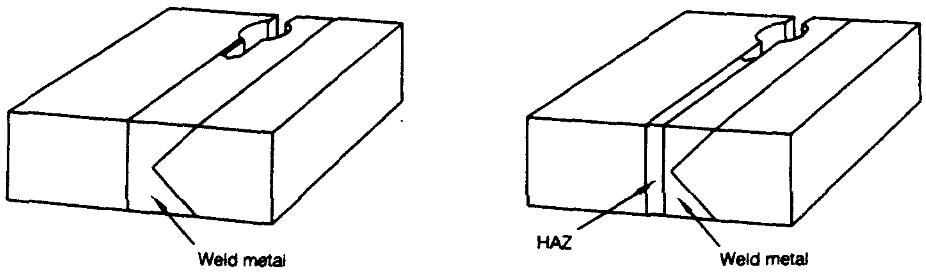


Figure 4: Weld pass interaction on a multipass K-preparation weld. (material: BIS 812 EMA, etchant: nital)

3. Notch Tip Location

The weld preparation selected for determining arrest toughness of the weld metal and HAZ is the K-prep. as shown in Figure 2. The K-prep. weld is not used in the fabrication of submarine hull segments but has been used in this work to allow the notch tip of the specimen to be positioned in the weld metal or HAZ and encourage crack propagation entirely within that microstructure as illustrated in Figure 5. For weld metal specimens, the notch is positioned in the centre of the weld and for HAZ specimens, 1 to 2 millimetres from the fusion boundary.

Figure 6 illustrates how the weld metal and HAZ regions are located for positioning of the crack starter notch. The specimen is machined to size except for the 2H dimension which is deliberately kept oversize. The end faces of the specimen are etched to show the weld profile, allowing the weld metal and HAZ to be identified. Once these regions have been identified the notch can be positioned and the 2H dimension reduced to that of the ASTM specification for assessment of crack arrest fracture toughness [5].



(a) *(b)*

Figure 5: Positioning of K_{Ia} specimen notch with respect to (a) weld metal and (b) heat affected zone.

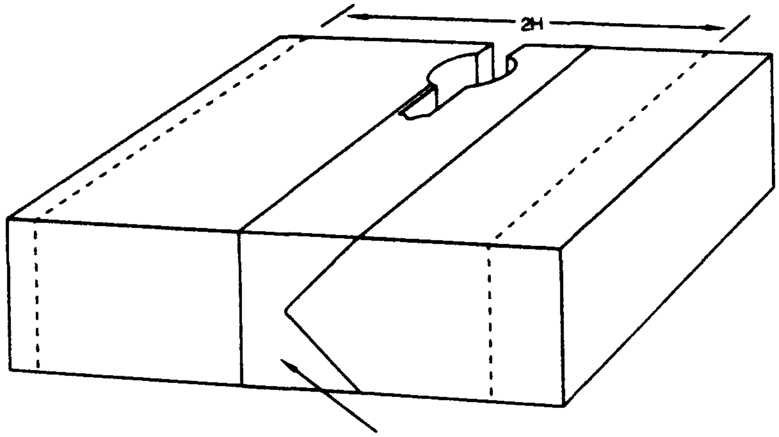


Figure 6: Oversize K_{Ia} specimen showing finished specimen size indicated by dashed lines.

4. Crack Arrest Test Procedure

The specimen used for determining crack arrest fracture toughness, shown in Figure 7, differed slightly from the recommended test specimen configuration in ASTM E1221 [5]. The W/B (specimen width to thickness) ratio recommended by ASTM E1221 was decreased from 4 to 2 and the face groove depth was reduced from Bn/B = 0.75 (B = specimen thickness and Bn = nett thickness of the specimen at the face grooves) to (i) Bn/B = 0.88 and (ii) Bn/B = 1.0. A reduction in the W/B ratio allowed specimens of full plate thickness to be used without increasing the other specimen dimensions which may have required load levels greater than the test machine capacity, while earlier work [3] showed face grooves of the recommended depth of Bn/B = 0.75 caused a number of specimens to fracture into two. A reduction in face groove depth has been shown [6] to produce a reduction in blunt notch initiation toughness, K_o, which lowers the level of stored elastic strain energy prior to fracture. This reduction in strain energy reduces the total energy available for crack propagation, increasing the probability of cracks arresting within the specimen. Changing face groove depth also alters the propagating crack velocity which may affect the crack arrest fracture toughness.

The expression used to calculate the stress intensity factor following arrest for this work is that of Underwood and Newman [7], given in Equation 1, while the expression given in ASTM E1221 is derived from the experimental compliance results of Crosley and Ripling [8].

The nature of experimental compliance results include plastic zone size effects which are significant at larger a/W values. The Underwood and Newman calibration approached the deep crack limit solution for this specimen [9] and is more accurate over the full range of a/W.

$$K = Y(1 - a/W)^{1/2}\delta E\,(B/Bn)^{1/2}/W^{1/2} \qquad (1)$$

where

$$Y = 0.748 - 2.76\, a/W + 3.56\, (a/W)^2 - 2.55\, (a/W)^3 - 0.62\, (a/W)^4$$

for the range $0.2 < a/W < 1.0$

where
E = Young's modulus
δ = crack mouth opening displacement
a = crack length
W = specimen width
B = specimen thickness
Bn = net specimen thickness at face grooves

The crack mouth opening displacement is measured a distance W/4 from the load line in order to use either of the above calibrations. Measurement is accomplished using a clip gauge as described in ASTM E399 [10].

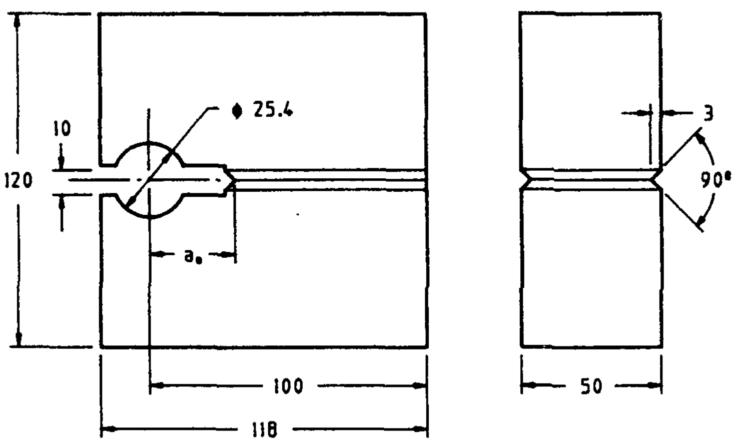


Figure 7 : K_{Ia} specimen dimensions (showing 3 mm deep face grooves per side).

In specimens where crack extension and arrest has occurred, crack length measurements are facilitated by heat tinting. After the propagating crack has arrested, the specimen is heated in an electric furnace at 400°C allowing a blue oxide film to form on the fracture faces. The specimen is then re-loaded and fractured into two using the wedge loading method, this allows direct measurement of the crack jump length.

5. Crack Arrest Toughness Test Program

For the parent plate, tests were conducted on specimens from the T-L orientation, with and without face grooves at nominal temperatures of -60°C and -80°C. Specimens from the weld metal and HAZ regions, with and without face grooves, were tested at the nominal temperatures -60°C, -80°C, -100°C and -120°C. These specimens were machined from coupons with the weld metal parallel to the rolling direction. Face grooves of 6% (3 mm) of specimen thickness per side were used to alter propagating crack velocity and additionally determine what affect this may have on the crack arrest fracture toughness.

6. Results

Tabulated results of K_{Ia} tests on BIS 812 EMA parent plate, heat affected zone and weld metal are given in Tables 3, 4 and 5 respectively. Of eleven tests performed on specimens from the weld metal region, three produced a crack initiation and propagation event and of eleven samples from the heat affected zone, nine resulted in initiation and propagation events. Six out of the eight specimens from the parent plate produced appreciable crack jumps.

Specimens from the weld and heat affected zone which did not produce crack initiation had the notch depth increased and were re-tested. This procedure was carried out to remove any plastic zone due to the initial loading. The results of the re-tests appear in Table 6. The plastic zone size was calculated using Equation 2 [11] and the maximum plastic zone size of any unfractured specimen was found to be 20 mm. For ease of machining, all unfractured specimen notches were increased in depth by this amount.

$$\text{plastic zone radius} = (K_I^2/ys^2)/2\pi \qquad (2)$$

Table 3: Results of K_{Ia} tests on BIS 812 EMA parent plate steel.

Specimen num.	Face groove depth mm	Temperature °C	a_o/W	a_f/W	K_o (Ref.7) MPa√m	K_a MPa√m	Valid
5	-	-57	0.375	0.899	253	68	No
6	-	-57	0.375	0.853	199	74	Yes
1	3	-60	0.285	0.427	173	-	No
2	3	-60	0.375	0.428*	285	-	No
3	-	-73	0.375	0.775	130	63	Yes
4	-	-76	0.375	0.852	151	59	Yes
8	3	-80	0.375	0.943	153	33	No
7	3	-81	0.440	1.000	144	-	No

* Crack did not propagate in parent material, traversed brittle weld bead only. K_{max} value indicated.

In some cases crack propagation did not always occur in the required plane, this is most noticeable in specimens from the weld metal and HAZ regions where the crack deviates from the desired path and the crack tip stress intensity can no longer be described by the mode I crack arrest fracture toughness parameter. Crack arrest fracture toughness values were not determined from these crack propagation and arrest events.

Unfractured ligaments on the fracture surface of specimens may restrict the amount of crack opening displacement and underestimate the arrest toughness. Specimens from the weld metal and HAZ regions produced a greater amount of ligamentation than the parent plate specimens and this is most probably due to the lack of microstructural uniformity across the crack paths in the weld metal and HAZ. Although some ligamentation was encountered, none appeared to be a significant criteria for invalidating results when compared to the guidelines in ASTM E1221.

For all specimens tested, some crack extension occurred. When significant crack growth did not occur, the initial crack extension arrested at the crack starter weld bead/test material interface. Crack arrest toughness results were not obtained from these tests.

Table 4: *Results of K_{Ia} tests on BIS 812 EMA heat affected zone.*

Specimen num.	Face groove depth	Temperature	a_o/W	a_f/W	K_o	K_a	Valid
					(Ref. 7)		
	mm	°C			MPa√m		
9	-	-58	0.375	*	272	-	No
18	3	-76	0.375	0.810	223	101	Yes
19	3	-79	0.370	0.543	123	84	No
19	3	-72	0.543	0.925	180	66	No
14	-	-78	0.375	0.918	171	46	No
15	-	-78	0.372	0.662	172	105	Yes
13	3	-100	0.375	0.632	129	79	No
17	3	-105	0.375	0.575	107	76	No
16	-	-103	0.375	0.577	108	79	No
10	-	-99	0.375	*	200	-	No
11	3	-120	0.375	0.755	132	66	No
12	3	-125	0.375	0.512	84	66	No

* Crack did not propagate, traversed brittle weld bead only. K_{max} value indicated.

Table 5: Results of K_{Ia} tests on BIS 812 EMA weld metal.

Specimen num.	Face groove depth mm	Temperature °C	a_o/W	a_f/W	K_o	K_a (Ref.7) MPa√m	Valid
22	3	-78	0.375	*	240	-	No
20	-	-95	0.375	*	279	-	No
28	3	-97	0.375	*	273	-	No
23	3	-98	0.375	0.853	204	82	Yes
24	3	-98	0.375	*	273	-	No
30	3	-100	0.375	1.000	238	-	No
21	-	-100	0.375	*	262	-	No
26	-	-116	0.375	*	231	-	No
29	3	-121	0.375	1.000	250	-	No
27	-	-123	0.375	*	211	-	No

* Crack did not propagate, traversed brittle weld bead only. K_{max} value indicated.

Table 6: Results of re-tests carried out on specimens from the HAZ and weld metal regions.

Specimen num.	Face groove depth mm	Temperature °C	a_o/W	a_f/W	K_o	K_a (Ref.7) MPa√m	Valid
10	-	-84	0.580	0.827	158	95	Yes
9	-	-100	0.600	0.877	126	65	No
22	3	-78	0.610	1.000	209	-	No
27	-	-80	0.605	*	264	-	No
25	-	-85	0.585	*	252	-	No
24	3	-90	0.575	*	272	-	No
21	-	-91	0.610	*	253	-	No
28	3	-101	0.605	1.000	192	-	No
20	-	-102	0.595	*	241	-	No
26	-	-103	0.575	*	211	-	No

* Crack did not propagate, traversed brittle weld bead only. K_{max} value indicated.

6.1 Parent Plate

K_{Ia} tests on parent plate material consisted of two specimens at each of the following temperature/geometry combinations, (a) -60°C with 3 mm deep face grooves, (b) -60°C without face grooves, (c) -80°C with 3 mm face grooves and (d) -80°C without face grooves. Eight specimens from the parent plate were tested and three valid K_{Ia} measurements were obtained. The test results are detailed in Table 3.

Specimens numbered 1 and 2 (-60°C, 3 mm deep face grooves) produced short diagonal crack jumps as seen in Figures 8a and 8b respectively, but the amount of crack extension was less than the minimum required for a valid result. The crack in specimen numbered 2 traversed the brittle weld only.

Tests on specimens numbered 5 and 6 (-60°C, no face grooves) produced substantial crack jumps but only specimen number 6 produced a crack that arrested below the maximum crack jump length specified in ASTM E1221 [5]. Specimen 6 met all of the validity criteria and had a K_{Ia} of 74 MPa$\sqrt{m}$.

Specimens numbered 7 and 8 (-80°C and 3 mm face grooves) had crack jump lengths that were excessive and therefore invalid. Specimen number 7 fractured into two.

The final two specimens from the parent plate, numbered 3 and 4 (-80°C, no face grooves) produced acceptable crack jumps and had K_{Ia} values of 63 and 59 MPa$\sqrt{m}$ respectively.

(a) (b)

Figure 8: Fracture faces and profiles of parent plate specimens; (a) specimen 1 (-60°C, 3 mm deep face grooves) and (b) specimen 2 (-60°C, 3 mm deep face grooves).

6.2 *Heat Affected Zone*

Specimens used to determine the arrest toughness of the heat affected zone are identified by the numbers 9 through 19. Of the eleven specimens tested from this region, nine produced propagation and arrest events and two did not produce any crack initiation. The two specimens (numbered 9 and 10) which failed to produce significant crack extension had their crack starter notches increased from an a/W of 0.375 to 0.575 and were re-tested. Both re-tests resulted in significant crack jumps, one valid and one invalid due to excessive crack extension. Details of test results on specimens from the HAZ are given in Table 4 and re-test results in Table 6.

Specimens numbered 9 (-58°C, no face grooves) and 10 (-99°C, no face grooves) failed to produce crack propagation while specimens numbered 14 (-78°C, no face grooves) and 19 (-72°C, 3 mm deep face grooves) were invalid due to excessive crack extension. Of the remaining seven specimens, only specimens numbered 15 (-78°C, no face grooves) and 18 (-76°C, 3 mm deep face grooves) were valid (K_{Ia} value of 105 and 101 MPa$\sqrt{m}$ respectively). The fractures in the other remaining specimens exhibited out of plane crack extension and were invalid, the profile of specimen number 12 seen in Figure 9, clearly illustrates the out of plane crack extension behaviour. The specimen numbered 19 (-79°C, 3 mm deep face grooves) was tested twice; the initial crack extension was thought to be too shallow to give a valid result, and was re-loaded (at -72°C) to produce a larger crack extension. The second crack extension exceeded the maximum allowed and was also invalid. Crack extension in this specimen was also out of plane.

Specimens 9 and 10 produced crack initiation and arrest events when re-worked and re-tested. Specimen 9 was re-tested at -101°C and specimen 10 at -84°C, the results of these tests can be seen in Table 6. Specimen 10 produced a valid K_{Ia} value of 95 MPa$\sqrt{m}$ while specimen 9 was invalid due to excessive crack extension.

Figure 9: Fracture face and profile of heat affected zone specimen number 12 (-125°C, 3 mm deep face grooves) showing out of plane crack extension.

Figure 10 illustrates ligamentation that has occurred in specimen 18 and is identified by the lighter areas in the crack propagation region. The material in these areas did not fracture during the initial crack propagation and consequently did not oxidise in the heat tinting operation. Specimen 18 exhibited the most severe ligamentation in specimens from the HAZ although in comparison with examples in ASTM E1221, were not severe enough to be considered invalid.

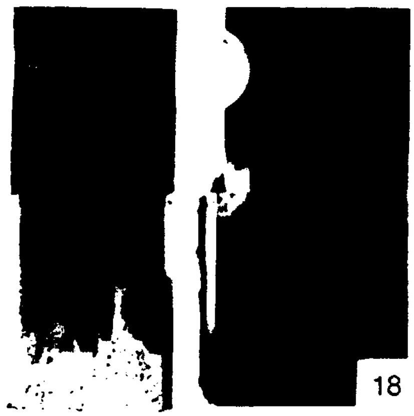


Figure 10: Specimen 18 (-76°C, 3 mm deep face grooves) taken from the HAZ showing ligamentation in the crack propagation region.

6.3 Weld Metal

The tests on specimens from the weld metal (specimens numbered 20-30) produced three crack propagation events but only one valid arrest result was obtained. The temperature range varied between -80°C and -120°C and tabulated results of the tests can be seen in Table 5. The specimen numbered 23 (-100°C, 3 mm deep face grooves) was the only specimen to produce a valid crack arrest fracture toughness with a value of 82 MPa√m. The other specimens to produce a propagation event, numbers 29 (-120°C, 3 mm face grooves) and 30 (-100°C, 3 mm face grooves) fractured completely during the test with the crack in specimen 29 propagating out of the plane.

Table 6 lists results from re-worked and re-tested specimens from the weld metal region. Of the eight specimens from the welded region which were re-worked and re-tested, only two produced an initiation event but the cracks propagated through the remaining ligaments, completely fracturing both specimens. Crack extension in these specimens remained in plane. The six unfractured specimens all produced cracks in the crack starter weld bead, but these cracks terminated at or near the fusion boundary of the crack starter weld bead.

7. Discussion

Comparison of K_{Ia} results from crack arrest fracture toughness tests on BIS 812 EMA parent plate, HAZ and weld metal show the weld procedure used by ASC did not have a deleterious effect on the crack arrest fracture toughness of this material. The test data, although incomplete, show the arrest toughness values of the HAZ and weld metal to be enhanced when compared to parent plate at equivalent temperatures.

At -80°C, the average K_{Ia} value for parent plate was 61 MPa√m while the average value for the HAZ was 100 MPa√m, an increase of 64%. At -100°C the value of arrest toughness for the weld metal was 82 MPa√m, even though comparisons with the parent plate or HAZ cannot be made at this temperature as no valid results for the parent plate or HAZ were obtained, the crack arrest fracture toughness of the weld metal at -100°C is superior to that of the parent plate at -80°C.

Testing of the parent plate was not carried out at -100°C because at -80°C crack extension virtually produced complete fracture and subsequent testing at lower temperatures would not be beneficial. Conversely, tests on the weld metal and HAZ specimens at higher temperatures (-60°C) provide initiation problems due to high initiation toughness levels at these temperatures.

Examination of the test results shows the expected trend of decreasing crack arrest fracture toughness with decreasing temperature. At -60°C the measured value of arrest toughness of the parent plate was 74 MPa√m while at -80°C it was 61 MPa√m.

The specimens from the weld metal region did not initiate fracture easily, this can be seen from the high blunt notch crack initiation stress intensity or K_Q values in Table 5, compared to the values for the HAZ specimens in Table 4. High blunt notch initiation toughness values produce high levels of stored elastic strain energy which is available for crack propagation. When initiation occurred, excess energy caused the specimen to fracture completely removing any change of obtaining a crack arrest fracture toughness measurement. This appears to be the dominant reason that only a single run arrest segment of crack extension was obtained from the weld metal region with four out of five crack initiation events (two from the initial tests and two from re-tests) resulting in complete specimen separation. For the compact tension specimen, size limitations may be a contributing factor in not obtaining an arrest event, a double cantilever beam specimen with its longer ligament length may facilitate an arrest by allowing the specimen to absorb more strain energy than the compact tension specimen.

The effect of face grooves on arrest toughness cannot be accurately assessed from the tests carried out in this work; the inconclusive result is due primarily to the limited number of valid data points obtained. The only specimens that can be compared are the two valid results from the HAZ at -80°C, the value for the 3 mm deep face grooved specimen was 101 MPa√m and 105 MPa√m for the non face grooved specimen. No statistical analysis can be undertaken but at least the results are self consistent, indicating no apparent effect on arrest toughness although other work by the author [3] on a similar steel showed a decrease in crack arrest fracture toughness measurement with increasing face groove depth.

The success of this series of tests to assess the crack arrest fracture toughness of BIS 812 EMA parent plate, weld metal and HAZ was also limited due to the restricted temperature range over which crack propagation and arrest events occurred. Crack arrest fracture toughness is however a quantitative arrest

toughness measurement on a laboratory scale in comparison to techniques such as that proposed by Robertson[12] which requires large scale specimens and test facilities and produces a crack arrest temperature rather than an assessment of the dynamic toughness of the material.

8. Conclusion

Structures such as ship hulls and submarine pressure hulls are fabricated using welding methods developed to achieve similar levels of strength and toughness as parent plate materials. The ability of a material to resist or halt propagating cracks is of prime importance in naval ships considering the implications of actions such as a weapons strike. If the dynamic fracture toughness of the HAZ and weld metal regions do not at least match those of the parent plate, from where the structural design emanates, a path of weakness exists that could lead to a catastrauphic failure if a crack were to initiate and propagate in one of these regions.

This work was undertaken to assess the dynamic toughness, measured by the crack arrest fracture toughness parameter, of BIS 812 EMA parent plate, HAZ and weld metal and compare the values to ensure compatability. The results show the arrest toughness of the HAZ and weld metal to be superior to that of the parent plate material indicating that the dynamic toughness of BIS 812 EMA is not diminished by the welding process employed by ASC in the fabrication of the Collins class submarine pressure hull. However, further testing would be necessary to generate sufficient data for a statistical analysis to confirm this result.

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TITLE

Evaluation of crack arrest fracture toughness of parent plate, weld metal and heat affected zone of BIS 812 EMA ship plate steel

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Steel   Crack arrest fracture toughness   Dynamic fracture toughness

ABSTRACT

The steel chosen for the pressure hull of the Collins class submarine has undergone evaluation to compare the crack arrest fracture toughness, K_{Ia}, of the parent plate with that of weld metal and heat affected zone. The tests were conducted over a range of sub-zero temperatures on specimens slightly outside the ASTM standard test method specimen configuration. Shallow face grooved specimens were used to vary the propagating crack velocity from that of non face grooved specimens and determine if K_{Ia} is sensitive to changes in crack velocity.

The weld metal, heat affected zone (HAZ) and parent plate were assessed to determine if the welding process had a deleterious effect on the crack arrest properties of this particular steel. Tests on each of these regions revealed that, for the combination of parent plate, welding procedure and consumables, no adverse effect on crack arrest properties was encountered. Crack arrest fracture toughness of the weld metal and HAZ was superior to that of the parent plate at comparable temperatures.

Evaluation of Crack Arrest Fracture Toughness of Parent Plate,
Weld Metal and Heat Affected Zone of BIS 812 EMA Ship Plate Steel

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(MRL-TR-93-9)

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